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Mars Exploration Rover

Challenges and Simulations of Mars-03 Terminal Descent

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Purpose of tRAD Performance Analysis



Mars Exploration Rover

- **Verifying performance of MER EDL system with tRAD**
 - **Successful implementation of tRAD with airbag inflation, RAD firing, bridle cut**
 - **Satisfactory surface impact conditions within airbag capability**
 - **Statistical tRAD performance verification under full range of possible conditions and uncertainties**
 - **Entry conditions**
 - **Environmental conditions (air density, wind, terrain)**
 - **Subsystem performance uncertainty (c.g. offset, RAD firing, altimeter)**
 - **Uncertainty in aerodynamic characteristics**
- **Studying key parameters affecting tRAD performance**
 - **Wind (no wind, step cross wind, wind shear)**
 - **Parachute stability**
 - **RAD thrust mismatch**
 - **RAD thrust misalignment**
 - **Backshell c.g. offset**
 - **Triple bridle confluence point offset**
- **Providing key data for EDL sub-system design and testing**
 - **Loads and clearance loss**
 - **tRAD and RAD firing tests**
 - **EDL system testing**

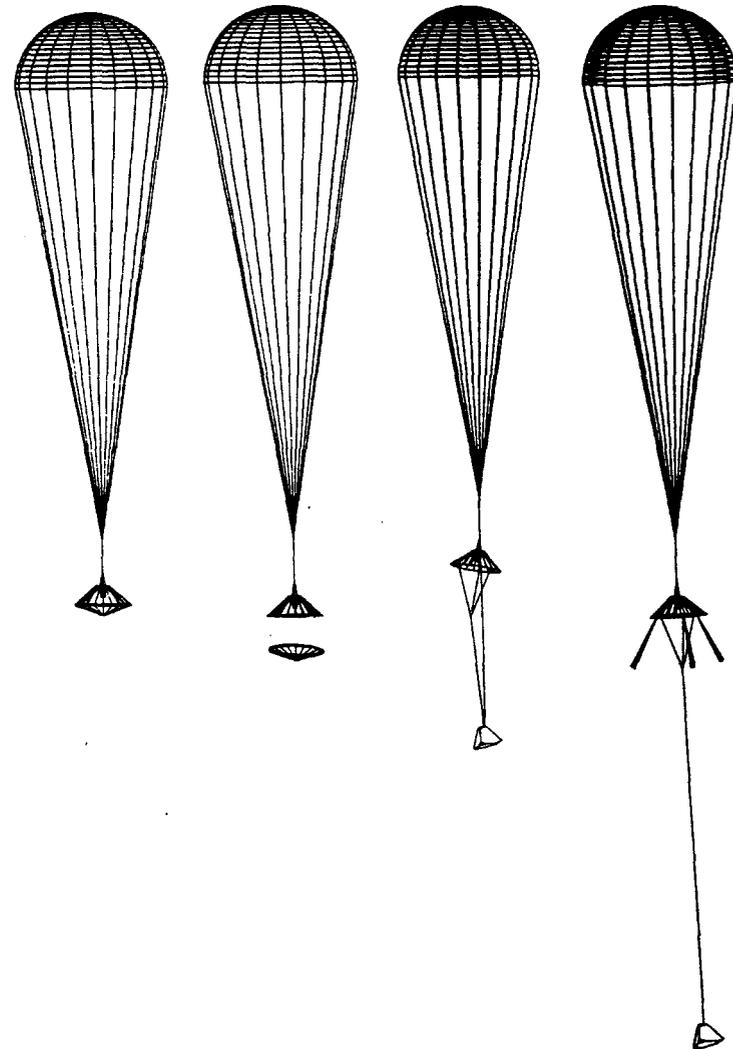


Multi-Body Dynamic Model

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- **Used a multi-body dynamic model developed in ADAMS to conduct tRAD performance analysis**
- **Based on the model developed for EDL System PDR (i.e. configuration of 775 kg entry/500 kg landing)**
- **Incorporated detailed 3-D multi-body mechanical dynamics and extensive input parameter dispersions**
- **Incorporated constrained tRAD timing and firing simulations after PDR**
- **Simulation covered time period from parachute deploy to ground impact**





Performance under Step Cross Wind



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- Cross wind was applied from the altitude of 0 to 500 m above ground.
- Wind magnitude remained constant vs. altitude: 10, 15, 20, 25 m/sec.
- Note that a very stable MPF type parachute was used.
- The following table is a results summary of eight simulation runs.

| Ground Impact Velocity (m/sec) | 10 m/sec wind | | 15 m/sec wind | | 20 m/sec wind | | 25 m/sec wind | |
|--------------------------------|---------------|-----------|---------------|-----------|---------------|-----------|---------------|-----------|
| | No tRAD | With tRAD |
| Magnitude | 20.1 | 9.9 | 24.2 | 11.3 | 27.9 | 13.9 | 31.5 | 17.1 |
| Vertical | 8.7 | 9.7 | 7.6 | 9.1 | 6.5 | 8.3 | 5.5 | 7.6 |
| Horizontal | 18.1 | 1.7 | 23.0 | 6.8 | 27.1 | 11.1 | 31.0 | 15.4 |

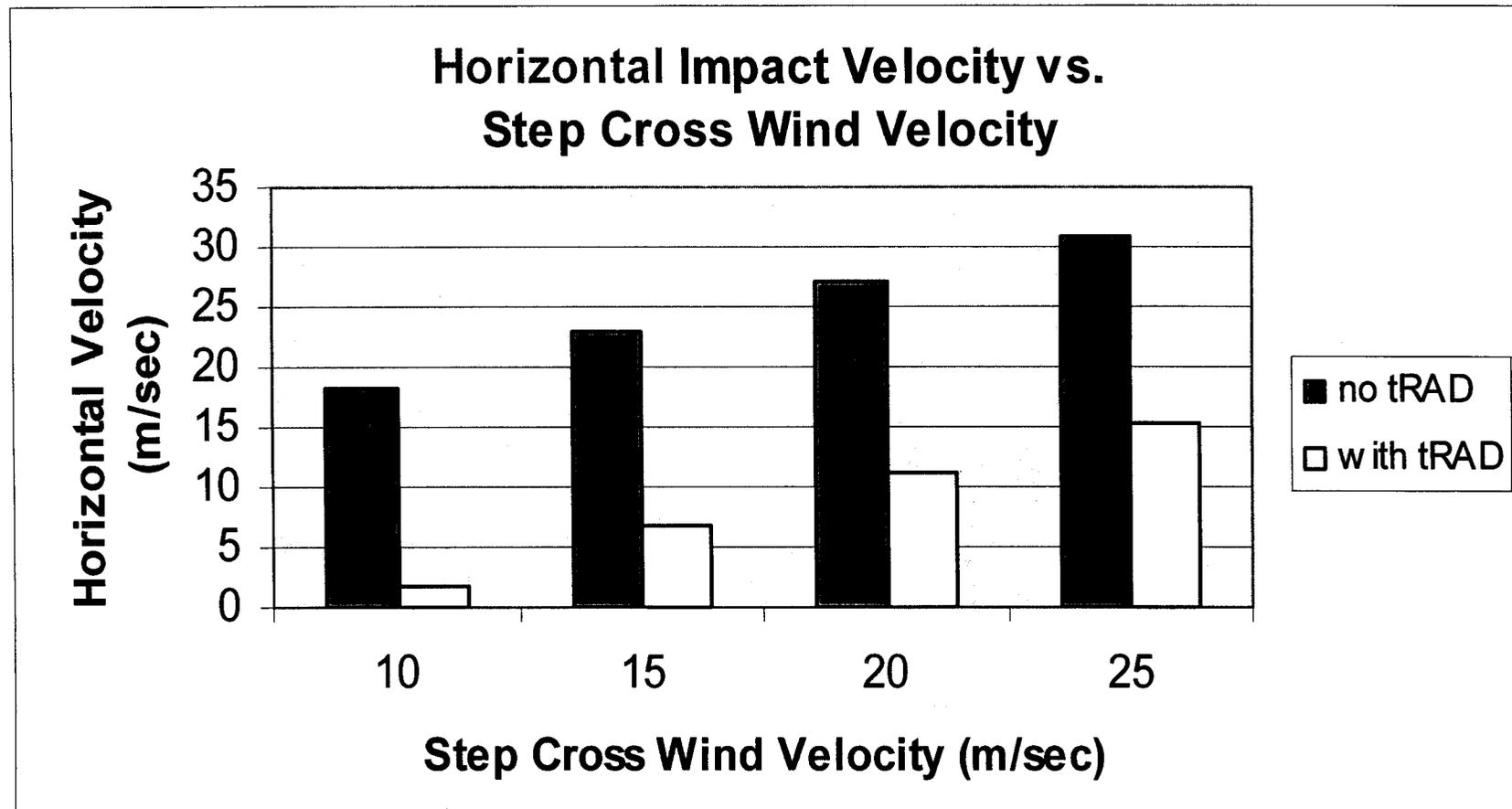


Performance under Step Cross Wind (cont.)



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- Current version of tRAD, i.e. constrained in both magnitude and direction, is capable of reducing RAD-induced horizontal velocities by ~16 m/sec independent of step cross wind velocities.



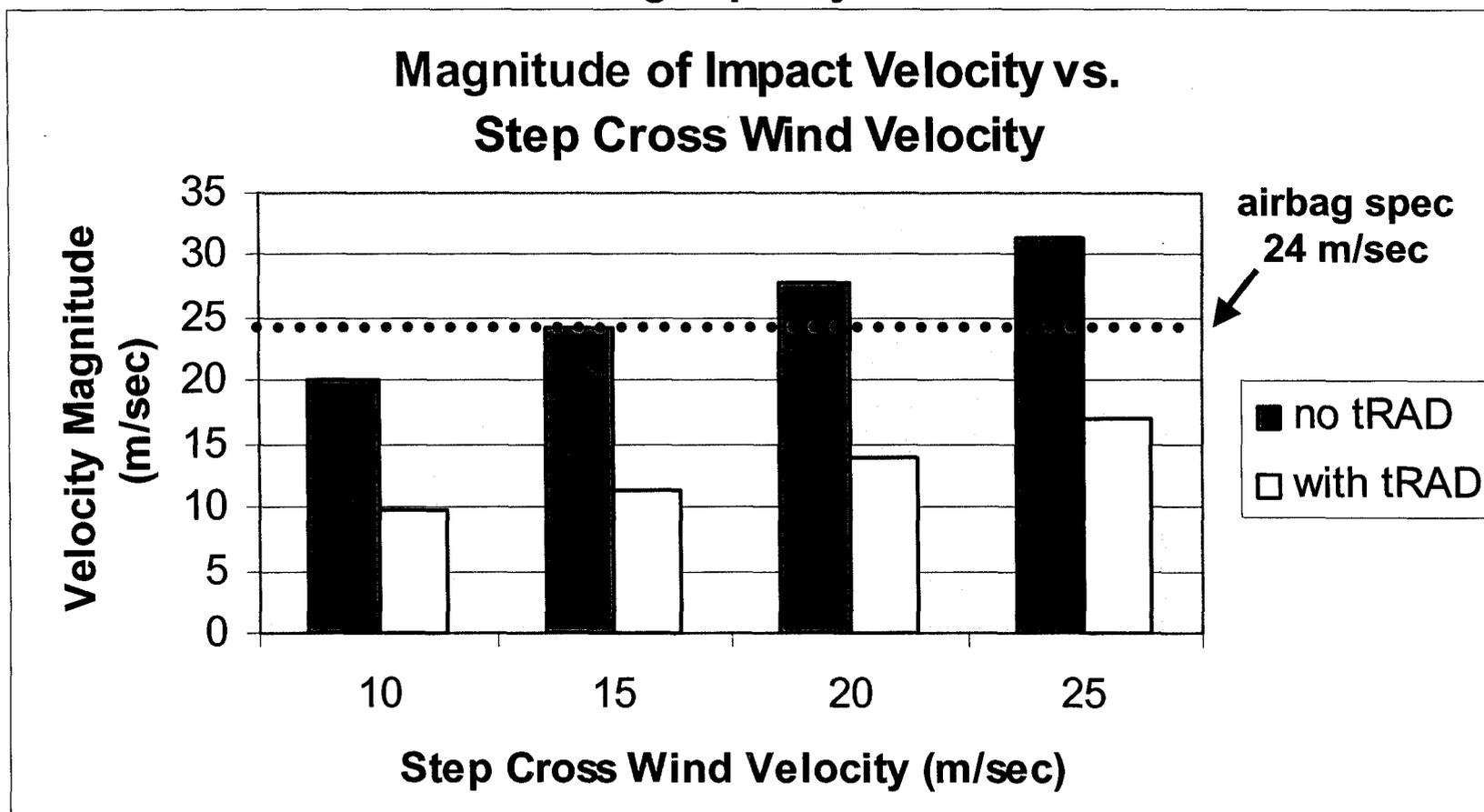


Performance under Step Cross Wind (cont.)

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- Without tRAD, impact velocity magnitudes will be out of airbag spec, 24 m/sec, when step cross wind velocities exceed 15 m/sec.
- With tRAD, impact velocity magnitudes are greatly reduced by ~50% and are well within the airbag capacity.





Performance vs. Parachute Stability/Wind



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- **Twelve multi-body Monte Carlo simulation studies were conducted.**
 - **No Wind vs. With Wind** (Using MPF wind profiles)
 - **Stable Chute vs. Unstable Chute** (To be conservative and to get the first order effect, the chute drag coefficients weren't changed vs. stability.)
 - **No tRAD vs. With tRAD**
 - **No Terrain Effect**

| Sim. ID | Wind | Chute Trim Angle | tRAD | RAD Thrust Profile | No. of Runs |
|---------|------|------------------|------|--------------------|-------------|
| 1 | No | 0 deg | No | Flat | 200 |
| 2 | No | 0 deg | Yes | Flat | 200 |
| 3 | No | 5 deg | No | Real | 200 |
| 4 | No | 5 deg | Yes | Flat | 200 |
| 5 | No | 10 deg | No | Real | 200 |
| 6 | No | 10 deg | Yes | Flat | 200 |
| 7 | Yes | 0 deg | No | Real | 200 |
| 8 | Yes | 0 deg | Yes | Flat | 200 |
| 9 | Yes | 5 deg | No | Real | 200 |
| 10 | Yes | 5 deg | Yes | Flat | 200 |
| 11 | Yes | 10 deg | No | Real | 200 |
| 12 | Yes | 10 deg | Yes | Flat | 200 |

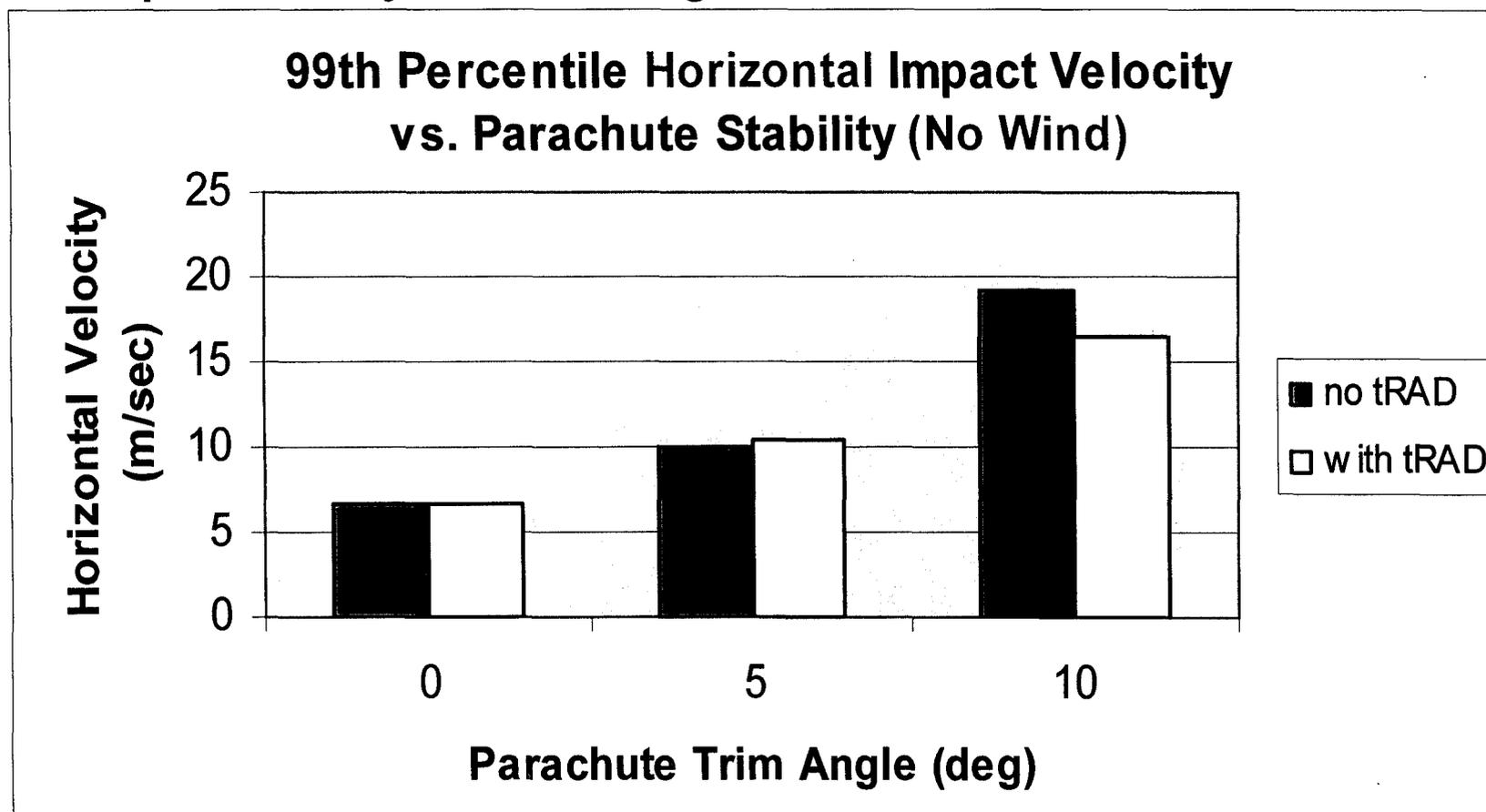


Performance w/o Wind vs. Parachute Stability



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- Under no wind condition, tRAD were not activated in most of runs resulting little difference between the runs with and w/o tRAD.
- Under no wind condition, note that the 99th percentile horizontal impact velocity can be as large as 19 m/sec for an unstable chute.



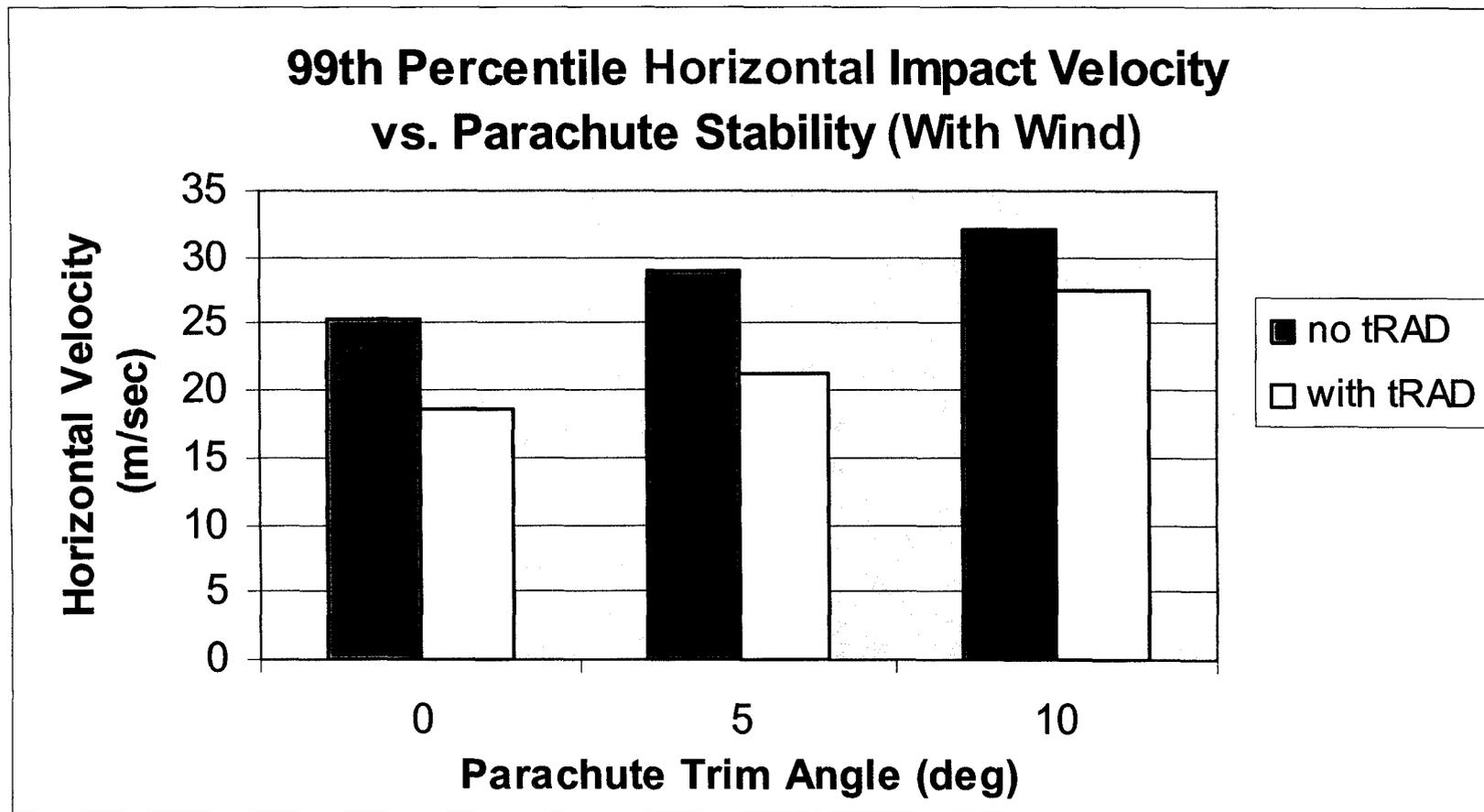


Performance with Wind vs. Parachute Stability



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- Under windy condition, tRAD reduces the 99th percentile horizontal impact velocities by at least 7-8 m/sec with a stable parachute.
- tRAD is less effective for an unstable chute of 10 deg trim angle.



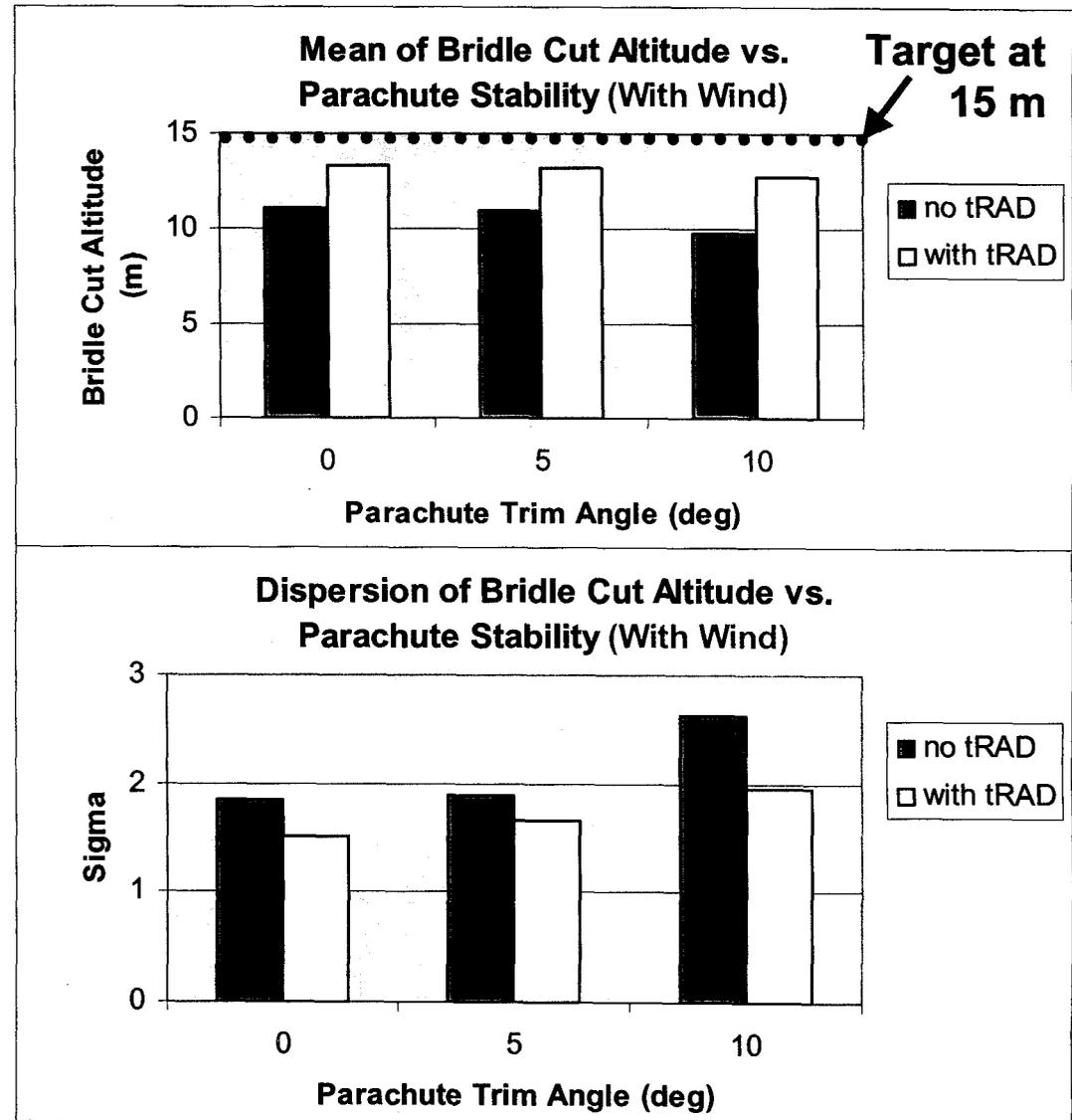


Performance with Wind vs. Parachute Stability (cont.)



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- Bridle tends to cut lower than target cut height with a less stable parachute.
- tRAD helps to bring mean bridle cut altitudes back to target cut height.
- Dispersion of bridle cut altitude increases with a less stable parachute.
- tRAD also helps to bring down bridle cut altitude dispersions.



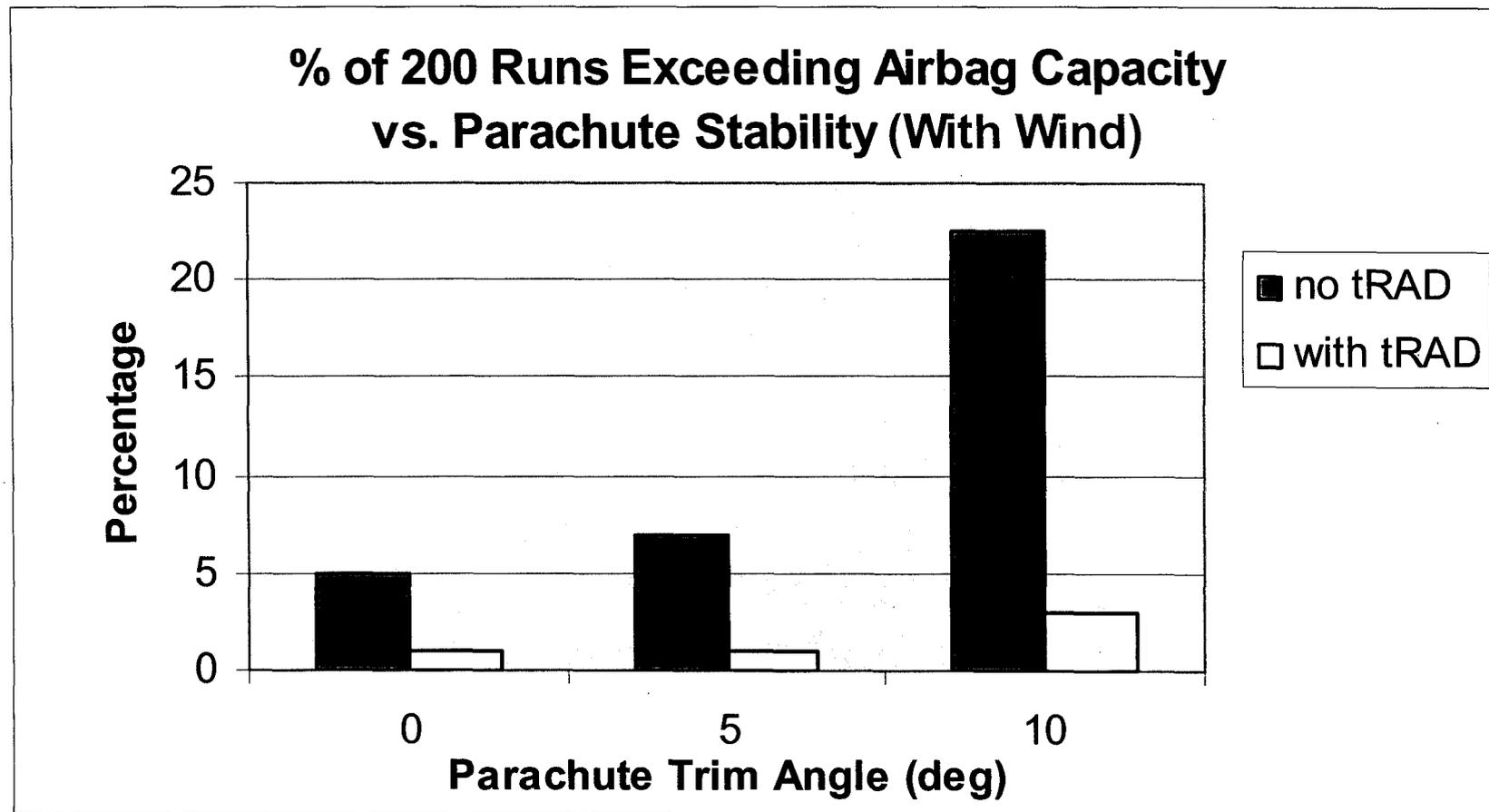


Performance with Wind vs. Parachute Stability (cont.)

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- The performance enhanced by tRAD is very apparent by examining the number of runs out of airbag spec at ground impact.
- With tRAD and a stable parachute, only 1% runs out of airbag spec.





Studies of Horizontal Impact Velocity Errors



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- **Horizontal impact velocity errors that can not be corrected by tRAD:**
 - RAD thrust mismatch
 - RAD thrust misalignment
 - Backshell c.g. offset
 - Triple bridle confluence point offset
- **Without the above errors, the 99th percentile horizontal impact velocity is 1.1 m/sec.**

| Parameter | Unit | 95% Value | 99% Value | Min. | Max. | Mean | 3-sigma |
|------------------------|------|-----------|-----------|--------|---------|---------|---------|
| Bridle Cut | | | | | | | |
| Time from Chute Deploy | sec | 136.727 | 139.997 | 89.694 | 148.067 | 118.666 | 30.4 |
| RAD Burn Time | sec | 3.478 | 3.58 | 2.899 | 3.673 | 3.248 | 0.456 |
| Height above Ground | m | 15.2 | 15.5 | 9.65 | 15.6 | 13.76 | 3.298 |
| Velocity Magnitude | m/s | 1.558 | 1.822 | 0.081 | 1.888 | 0.856 | 1.241 |
| Vertical Velocity | m/s | 0.137 | 0.403 | -1.775 | 0.997 | -0.702 | 1.533 |
| Horizontal Velocity | m/s | 0.846 | 1.074 | 0.025 | 1.357 | 0.302 | 0.729 |
| Ground Impact | | | | | | | |
| Time from Bridle Cut | sec | 3.296 | 3.401 | 2.093 | 3.425 | 2.93 | 0.744 |
| Velocity Magnitude | m/s | 10.777 | 10.896 | 8.489 | 10.935 | 10.176 | 1.309 |
| Vertical Velocity | m/s | 10.777 | 10.881 | 8.474 | 10.935 | 10.169 | 1.313 |
| Horizontal Velocity | m/s | 0.842 | 1.078* | 0.027 | 1.354 | 0.302 | 0.726 |



Horizontal Impact Velocity Error Due to RAD Thrust Mismatch



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- No wind, no tRAD, no thrust misalignments, no backshell c.g. offset, no triple bridle confluence point offset, no terrain effect.
- For a flat RAD burn profile, a thrust-to-thrust mismatch of +/- 2% (uniform distribution) is currently specified (C. Guernsey/E. Bailey).
- Based on the 99th percentile, a thrust mismatch of +/- 2% induces a horizontal impact velocity error of ~6 m/sec.

| Parameter | Unit | 95% Value | 99% Value | Min. | Max. | Mean | 3-sigma |
|------------------------|------|-----------|-----------|--------|---------|---------|---------|
| Bridle Cut | | | | | | | |
| Time from Chute Deploy | sec | 136.727 | 139.997 | 89.694 | 148.067 | 118.666 | 30.4 |
| RAD Burn Time | sec | 3.478 | 3.58 | 2.899 | 3.673 | 3.248 | 0.456 |
| Height above Ground | m | 15.8 | 16.32 | 9.24 | 16.79 | 13.772 | 4.123 |
| Velocity Magnitude | m/s | 5.059 | 6.174 | 0.264 | 6.406 | 3.16 | 3.682 |
| Vertical Velocity | m/s | 0.628 | 1.147 | -2.675 | 1.734 | -0.655 | 2.214 |
| Horizontal Velocity | m/s | 5.053 | 5.925 | 0.095 | 6.376 | 2.939 | 4.118 |
| Ground Impact | | | | | | | |
| Time from Bridle Cut | sec | 3.467 | 3.633 | 1.826 | 3.801 | 2.921 | 1.018 |
| Velocity Magnitude | m/s | 11.467 | 11.724 | 8.956 | 11.829 | 10.683 | 1.672 |
| Vertical Velocity | m/s | 11.027 | 11.232 | 8.313 | 11.459 | 10.181 | 1.639 |
| Horizontal Velocity | m/s | 5.054 | 5.916 | 0.097 | 6.361 | 2.936 | 4.11 |



Horizontal Impact Velocity Error Due to RAD Thrust Misalignment



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- No wind, no tRAD, no thrust mismatch, no backshell c.g. offset, no triple bridle confluence point offset, no terrain effect.
- Thrust misalignments are introduced in both RAD positions and orientations (A1: azimuth, A2: elevation) based on MPF EDL sim.

| | | Units | Distribution | Min. | Max. | Mean | 3-sigma |
|-------|----|-------|--------------|---------|---------|---------|---------|
| RAD-1 | X | m | uniform | -0.002 | 0.002 | 0.000 | 0.002 |
| | Y | m | uniform | 1.052 | 1.057 | 1.054 | 0.002 |
| | Z | m | uniform | -0.252 | -0.248 | -0.250 | 0.002 |
| | A1 | deg | normal | 179.433 | 180.652 | 180.006 | 0.653 |
| | A2 | deg | normal | 26.348 | 28.185 | 27.168 | 1.091 |
| RAD-2 | X | m | uniform | -0.915 | -0.911 | -0.913 | 0.002 |
| | Y | m | uniform | -0.529 | -0.525 | -0.527 | 0.002 |
| | Z | m | uniform | -0.252 | -0.248 | -0.250 | 0.002 |
| | A1 | deg | normal | 299.468 | 300.536 | 300.005 | 0.621 |
| | A2 | deg | normal | 26.215 | 28.309 | 27.178 | 1.150 |
| RAD-3 | X | m | uniform | 0.911 | 0.915 | 0.913 | 0.002 |
| | Y | m | uniform | -0.529 | -0.525 | -0.527 | 0.002 |
| | Z | m | uniform | -0.252 | -0.248 | -0.250 | 0.002 |
| | A1 | deg | normal | 59.377 | 60.564 | 60.016 | 0.672 |
| | A2 | deg | normal | 26.229 | 28.326 | 27.181 | 1.115 |



Horizontal Impact Velocity Error Due to RAD Thrust Misalignment (cont.)



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- Based on the 99th percentile, an error of ~2 m/sec in horizontal impact velocity can be induced by the RAD thrust misalignments of +/- 0.002 m in position, +/- 0.65 deg in azimuth angle, and +/- 1.12 deg in elevation angle.

| Parameter | Unit | 95% Value | 99% Value | Min. | Max. | Mean | 3-sigma |
|------------------------|------|-----------|-----------|--------|---------|---------|---------|
| Bridle Cut | | | | | | | |
| Time from Chute Deploy | sec | 136.727 | 139.997 | 89.694 | 148.067 | 118.666 | 30.4 |
| RAD Burn Time | sec | 3.478 | 3.58 | 2.899 | 3.673 | 3.248 | 0.456 |
| Height above Ground | m | 15.4 | 15.8 | 9.84 | 16.17 | 13.783 | 3.506 |
| Velocity Magnitude | m/s | 2.122 | 2.347 | 0.367 | | 1.344 | 1.441 |
| Vertical Velocity | m/s | 0.23 | 0.417 | -1.946 | 0.68 | -0.711 | 1.7 |
| Horizontal Velocity | m/s | 1.82 | 2.239 | 0.074 | 2.393 | 0.994 | 1.421 |
| Ground Impact | | | | | | | |
| Time from Bridle Cut | sec | 3.36 | 3.467 | 2.221 | 3.504 | 2.935 | 0.815 |
| Velocity Magnitude | m/s | 10.883 | 11.059 | 8.771 | 11.122 | 10.238 | 1.383 |
| Vertical Velocity | m/s | 10.859 | 11.005 | 8.557 | 11.108 | 10.179 | 1.404 |
| Horizontal Velocity | m/s | 1.816 | 2.231* | 0.073 | 2.39 | 0.993 | 1.416 |

* 99% value from nominal runs is 1.078 m/s



Horizontal Impact Velocity Error Due to Backshell C.G. Offset



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- No wind, no tRAD, no thrust mismatch, no thrust misalignments, no triple bridle confluence point offset, no terrain effect.
- Backshell c.g. (0,0,Z) are dispersed by +/- 0.05 m (B. Riggs); Large c.g. offset due to ballast uncertainties for EDL dynamic balance.
- Based on the 99th percentile, +/- 0.05 m backshell c.g. offset induces an error of ~5 m/sec in horizontal impact velocity.

| Parameter | Unit | 95% Value | 99% Value | Min. | Max. | Mean | 3-sigma |
|------------------------|------|-----------|-----------|--------|---------|---------|---------|
| Bridle Cut | | | | | | | |
| Time from Chute Deploy | sec | 136.751 | 140.147 | 89.617 | 148.022 | 118.663 | 30.384 |
| RAD Burn Time | sec | 3.478 | 3.581 | 2.899 | 3.672 | 3.247 | 0.457 |
| Height above Ground | m | 15.3 | 15.5 | 9.26 | 15.6 | 13.725 | 3.339 |
| Velocity Magnitude | m/s | 4.436 | 4.934 | 0.859 | 5.462 | 2.787 | 2.888 |
| Vertical Velocity | m/s | 0.202 | 0.586 | -1.755 | 1.028 | -0.638 | 1.609 |
| Horizontal Velocity | m/s | 4.435 | 4.926 | 0.28 | 5.43 | 2.616 | 3.231 |
| Ground Impact | | | | | | | |
| Time from Bridle Cut | sec | 3.267 | 3.394 | 2.02 | 3.409 | 2.909 | 0.769 |
| Velocity Magnitude | m/s | 11.052 | 11.256 | 9.228 | 11.284 | 10.542 | 1.132 |
| Vertical Velocity | m/s | 10.754 | 10.862 | 8.339 | 10.947 | 10.154 | 1.326 |
| Horizontal Velocity | m/s | 4.425 | 4.917* | 0.28 | 5.423 | 2.612 | 3.225 |



Horizontal Impact Velocity Error Due to Triple Bridle Confluence Point Offset



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- No wind, no tRAD, no thrust mismatch, no thrust misalignments, no backshell c.g. offset, no terrain effect.
- Triple bridle confluence point offset is introduced by varying the length of each triple bridle by +/- 0.125 in (A. Kapitanoff).
- Based on the 99th percentile, the triple bridle confluence point offset induces a horizontal impact velocity error of ~2 m/sec.

| Parameter | Unit | 95% Value | 99% Value | Min. | Max. | Mean | 3-sigma |
|------------------------|------|-----------|-----------|--------|---------|---------|---------|
| Bridle Cut | | | | | | | |
| Time from Chute Deploy | sec | 136.727 | 139.997 | 89.694 | 148.067 | 118.666 | 30.4 |
| RAD Burn Time | sec | 3.478 | 3.581 | 2.899 | 3.673 | 3.248 | 0.456 |
| Height above Ground | m | 15.2 | 15.5 | 9.58 | 15.7 | 13.755 | 3.33 |
| Velocity Magnitude | m/s | 2.077 | 2.377 | 0.113 | 2.666 | 1.383 | 1.361 |
| Vertical Velocity | m/s | 0.134 | 0.468 | -1.77 | 1.004 | -0.693 | 1.54 |
| Horizontal Velocity | m/s | 1.942 | 2.272 | 0.039 | 2.495 | 1.057 | 1.532 |
| Ground Impact | | | | | | | |
| Time from Bridle Cut | sec | 3.291 | 3.398 | 2.09 | 3.421 | 2.927 | 0.748 |
| Velocity Magnitude | m/s | 10.819 | 10.967 | 8.658 | 11.023 | 10.235 | 1.266 |
| Vertical Velocity | m/s | 10.784 | 10.882 | 8.45 | 10.933 | 10.166 | 1.318 |
| Horizontal Velocity | m/s | 1.93 | 2.267* | 0.041 | 2.49 | 1.057 | 1.529 |

* 99% value from nominal runs is 1.078 m/s